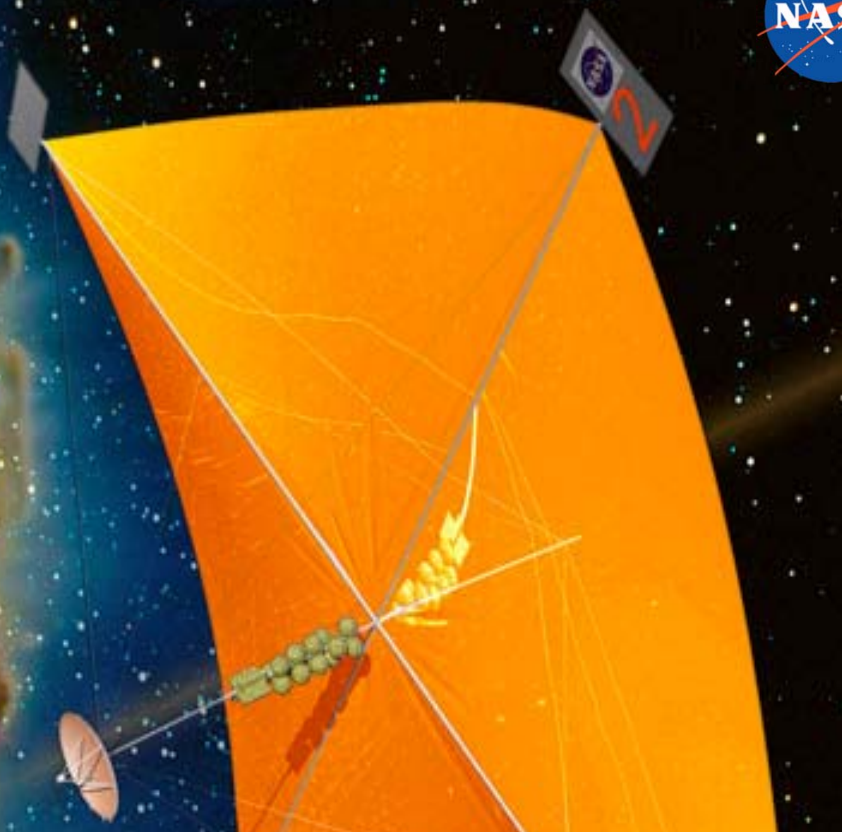
National Aeronautics and Space Administration

Solar Sails



In Space Propulsion Technology Project

NASA Marshall Space Flight Center

Roy Young

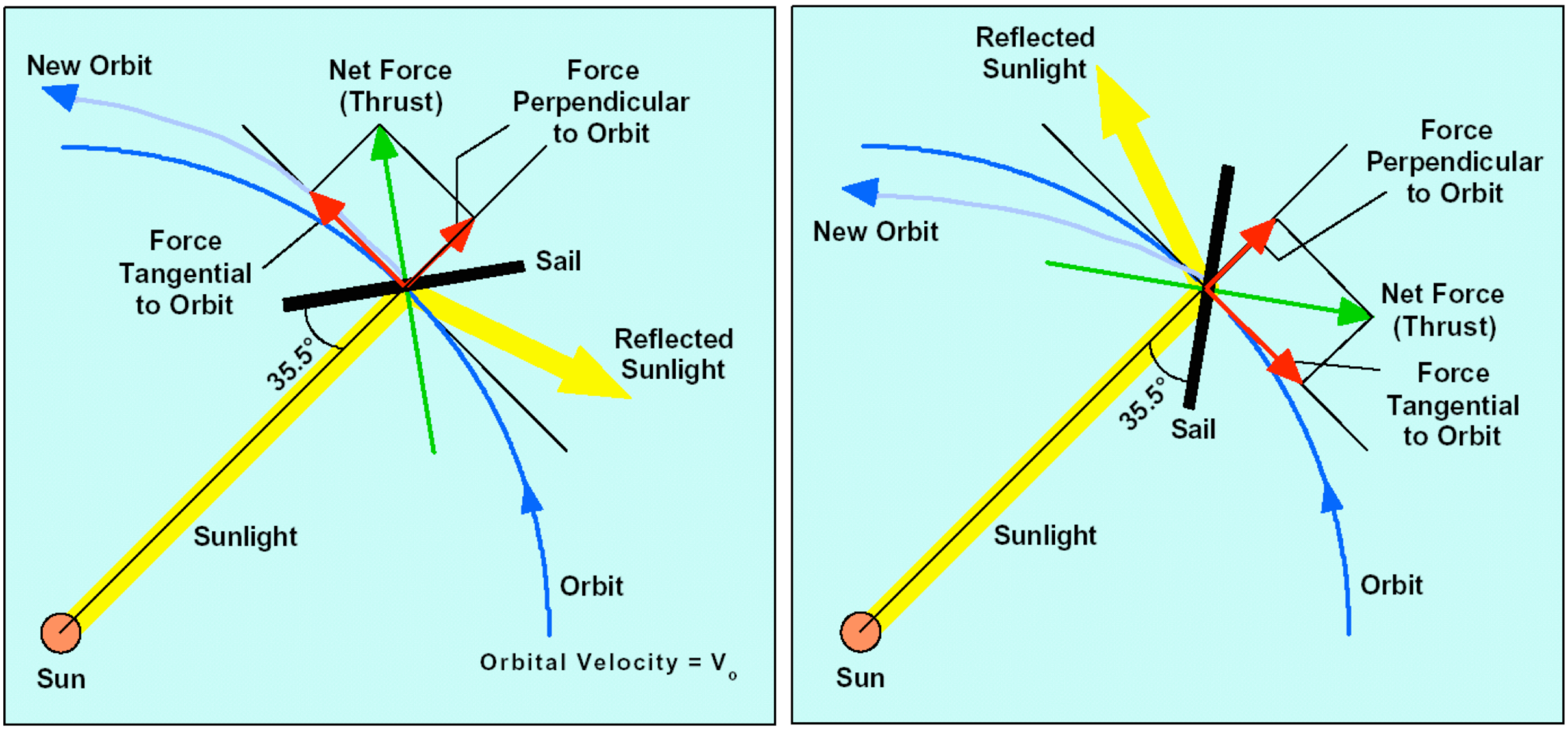
Earth Science Technology Conference 2006

June 27-29, 2006

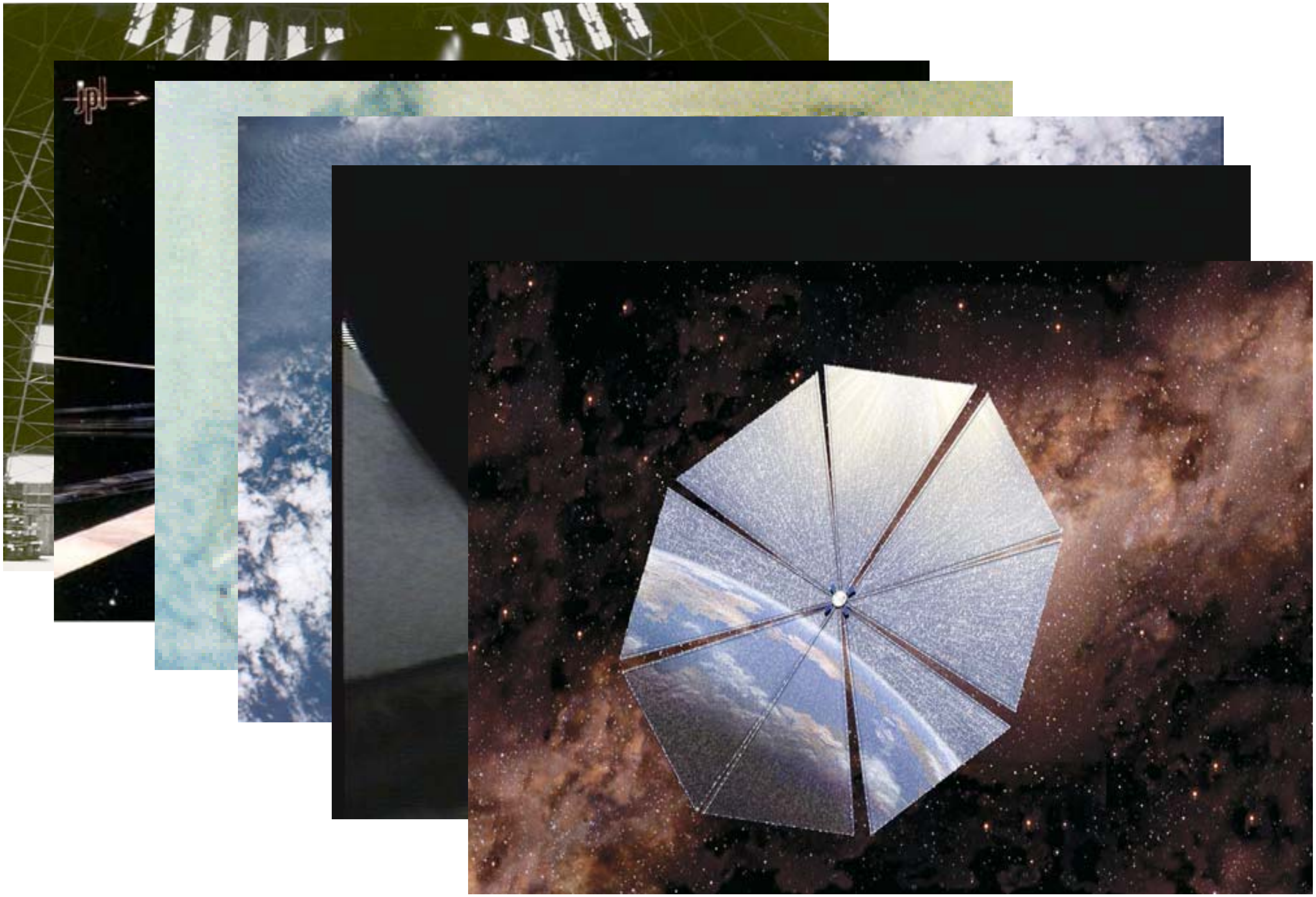

Technology Overview

Solar Sail Propulsion Fundamentals

- Solar sails use photon "pressure" on thin, lightweight reflective sheet to produce thrust; ideal reflection of sunlight from surface produces 9 Newtons/km^2 at 1 AU
- Net force on solar sail perpendicular to surface
- One component of force always directed radially outward
- Other component of force tangential to orbit (add/subtract V_o)



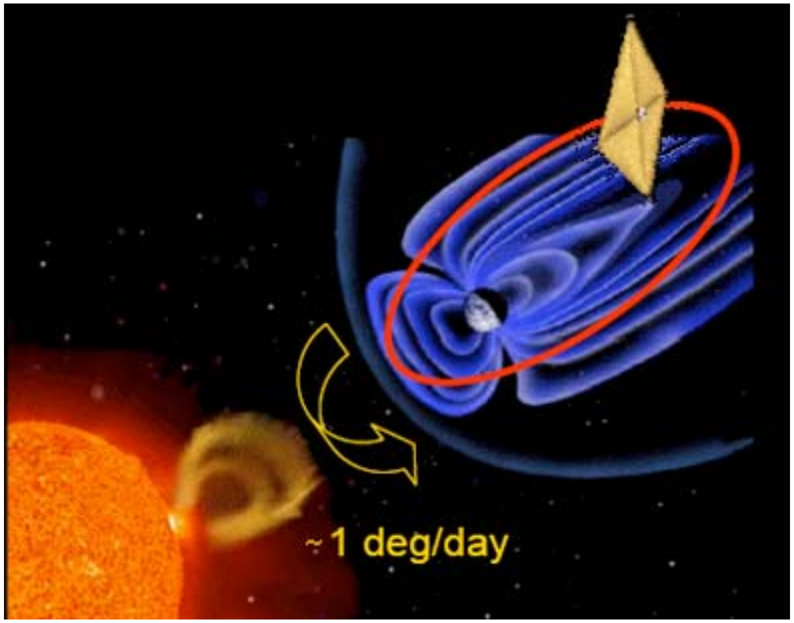
Solar Sail Heritage
(Big Shiny Things in Space)

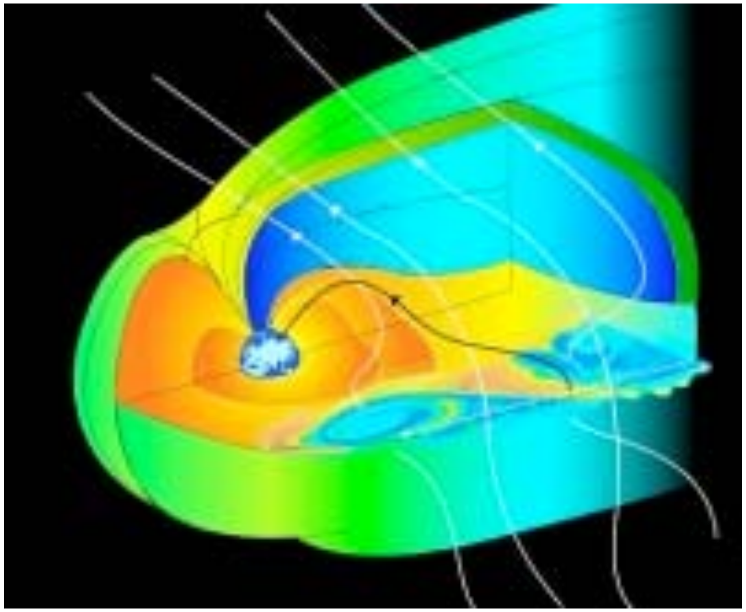


COSMOS - 2005

Missions Supported

GeoSail





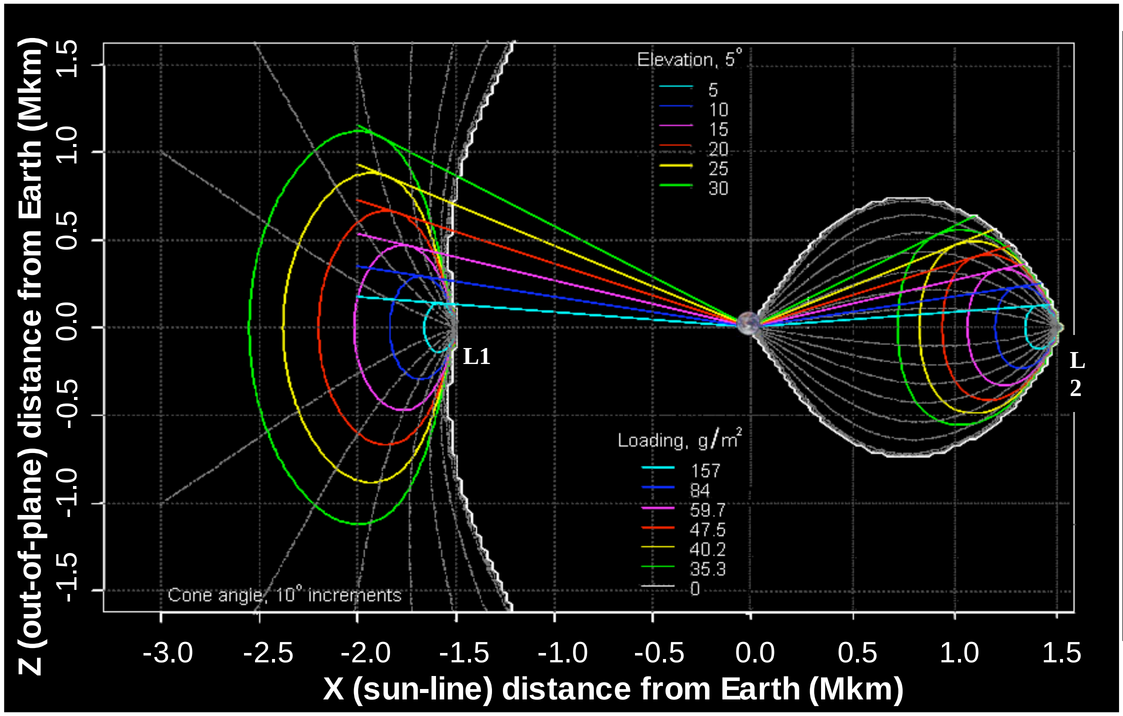
Science Objectives

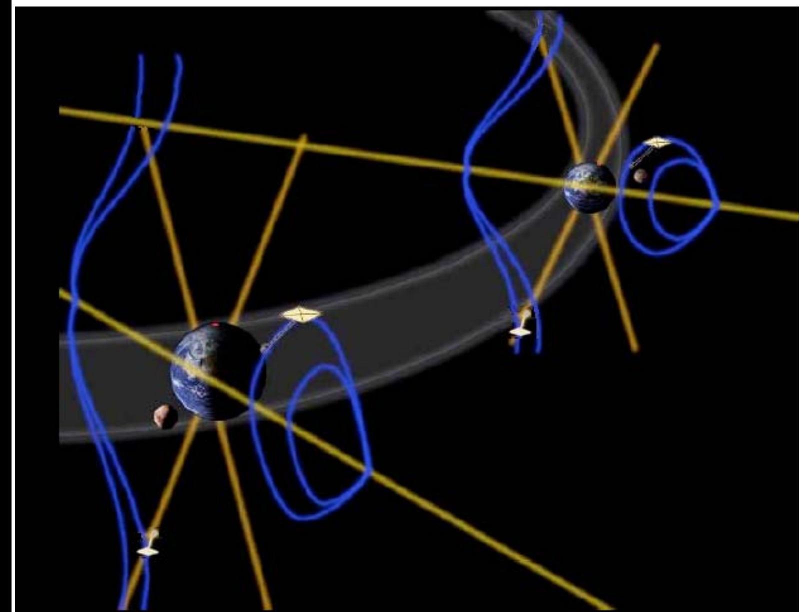
- **Understand how spontaneous magnetic reconnection occurs in a magnetic current sheet**
- **Understand the mechanism behind reconnection mode destabilization and saturation in the magnetotail**
- **Analyze the plasma structure at the sub-second resolution**
- **Understand reconnection and particle dynamics at the day/dawn side low-latitude boundary layer along the earth's magnetopause**

Mission Description

- **Precess orbit apsis line to stay permanently in Geomagnetic tail**
- **Launch direct to operational orbit (10 x 30 $_{ER}$), minimal mission if sail fails to deploy**
- **<u>40 m square sail @ 55 g/m^2 with characteristic acceleration ~ 0.1 mms^2</u>**
- **Demonstrate new science capability on technology demo mission**
- **Payload: magnetometers (2), electrostatic analyzer, solid state telescope (5 kg / 5 W or enhance 11 kg / 8.5 W)**

PoleSitter





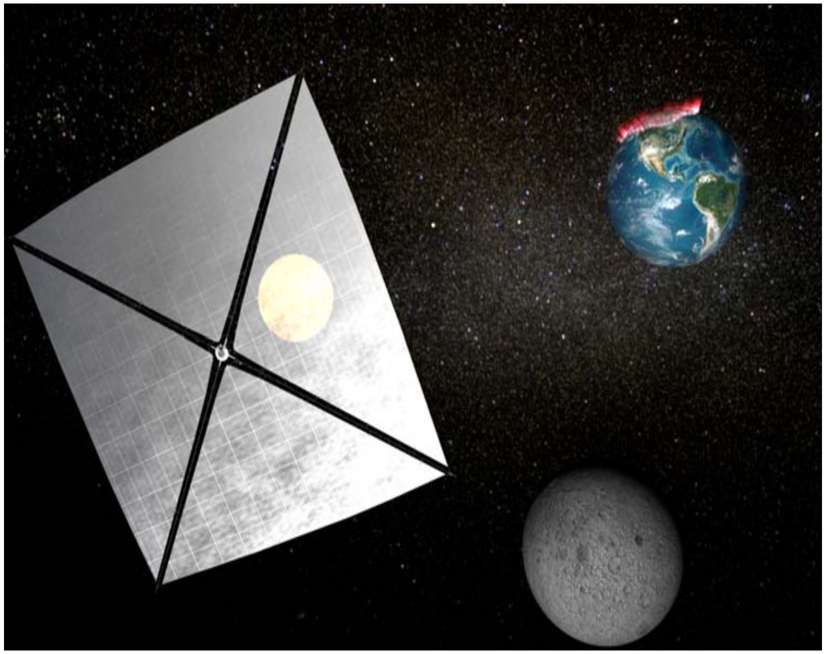
Polesitter Provides:

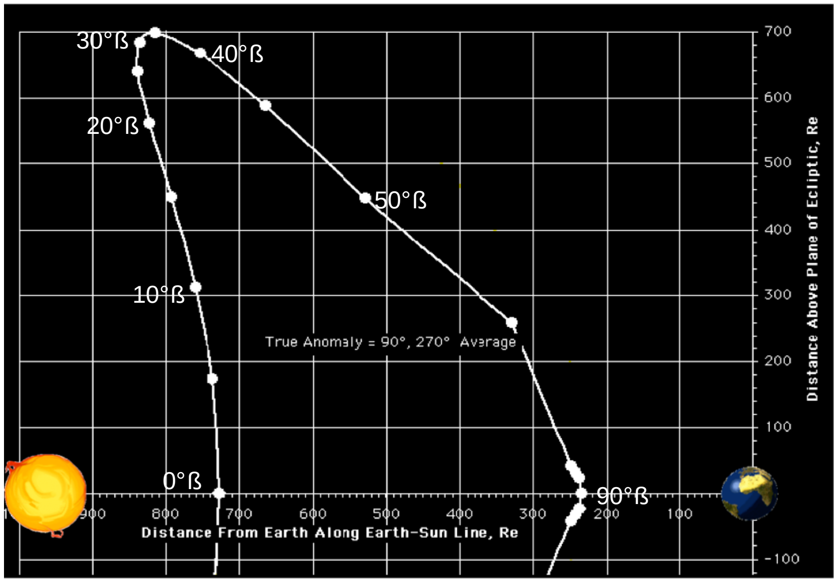
- **Near real-time imaging of Antarctic weather (Artic as well with sail at North L2 point)**
- **Data relay for the NPOESS satellite system**
- **Continuous communications/high speed data channel for Antarctic bases**
- **Solar sail areal density of 30 – 40 g/m^2, 0.23-0.3 mm^2 characteristic acceleration**

Polesitter Support of ESMD:

- **Slightly sunward of L1 for small increased leadtime for Coronal Mass Ejections (CMEs) warnings for Lunar astronauts.**
- **Continuous hemispheric visibility including Lunar south pole region for comm/high speed data.**

HelioStorm





Science Objectives

- **Understand the Sun-to-Earth evolution of CMEs, shocks and particle radiation from solar eruptions**
- **Remote- and local sense Earth-impacting solar disturbances**
- **Determine the structure of the solar wind on spatial and temporal scales that are relevant for driving magnetospheric processes**
- **Provide warning time to protect lunar and Earth-orbiting and ground assets**
- **Provide a demonstration platform for Exploration and a pathfinder for the Solar Polar Imager science mission**

Mission Description

- **Delta II Launch Vehicle**
- **Trajectory: ballistic transfer from Earth to L1 Halo (~90 days), solar sail transition from L1; <u>80m square sail @ 14.3 g/m2</u>**
- **Continuous Solar Viewing: 2 years In Final Orbit**
- **Flight System Concept**
- **Solar-array powered S/C with solar sail**
- **Payload: Fields and Particles+ Imaging (33 kg/24 W)**

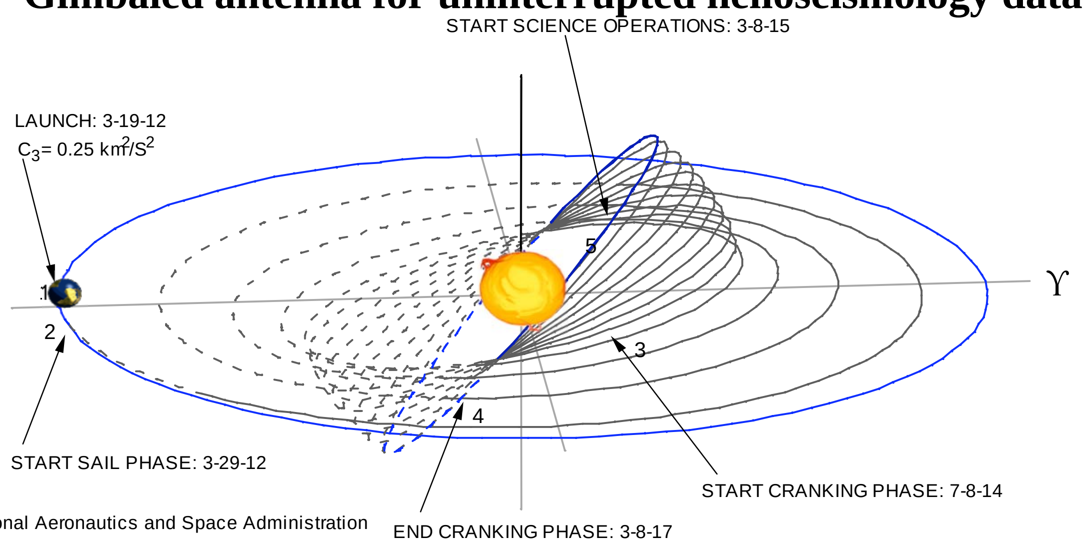
Solar Polar Imager (SPI)

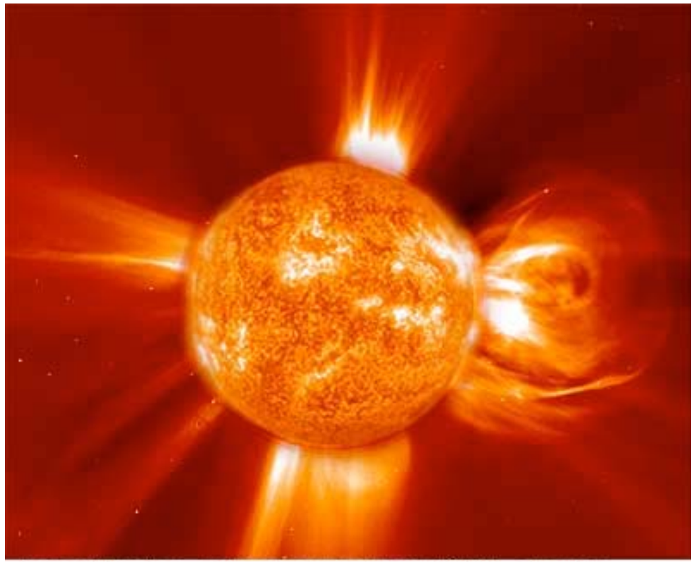
Science Objectives

- **What is the relationship between the magnetism and dynamics of the Sun's polar regions and the solar dynamo?**
- **What advantages does the polar perspective provide for space weather prediction?**
- **What is the azimuthal structure and dynamics of the corona and CMEs?**
- **How are variations in the solar wind linked to the Sun at all latitudes?**
- **How are solar energetic particles accelerated and transported in radius and latitude?**
- **How does the solar irradiance vary with latitude?**

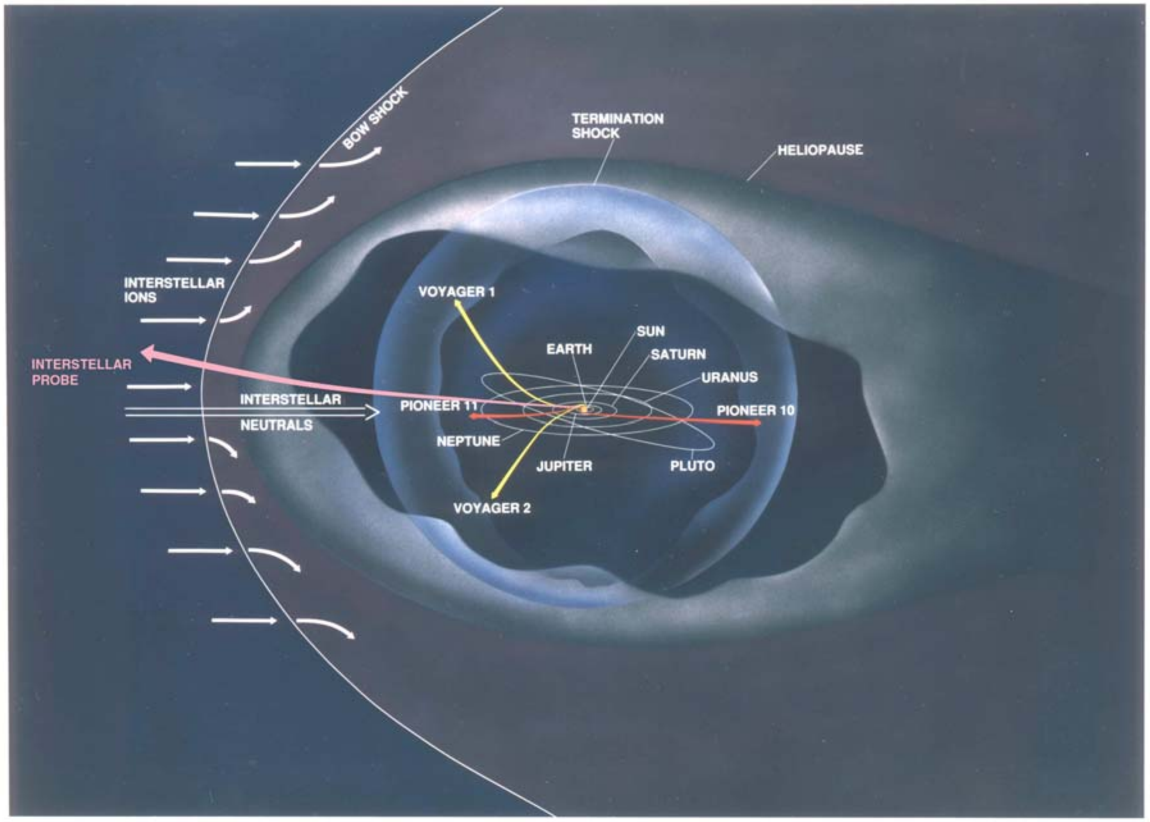
Mission Description

- **SC in highly inclined ~75° 3:1 resonant heliocentric 0.48 AU orbit**
- **Payload: Fields and Particles+ Imaging (44 kg/50 W, 34 kg/24.5 W)**
- **Uses solar sail to reach high inclination in 5-7 years; <u>150 m square sail @ 13 g/m2</u>**
- **Collect *in situ* data during cruise**
- **Average data rate > 60 kbps; store and dump, 2 passes/week**
- **Gimbaled antenna for uninterrupted helioseismology data**





Interstellar Probe



Mission Description

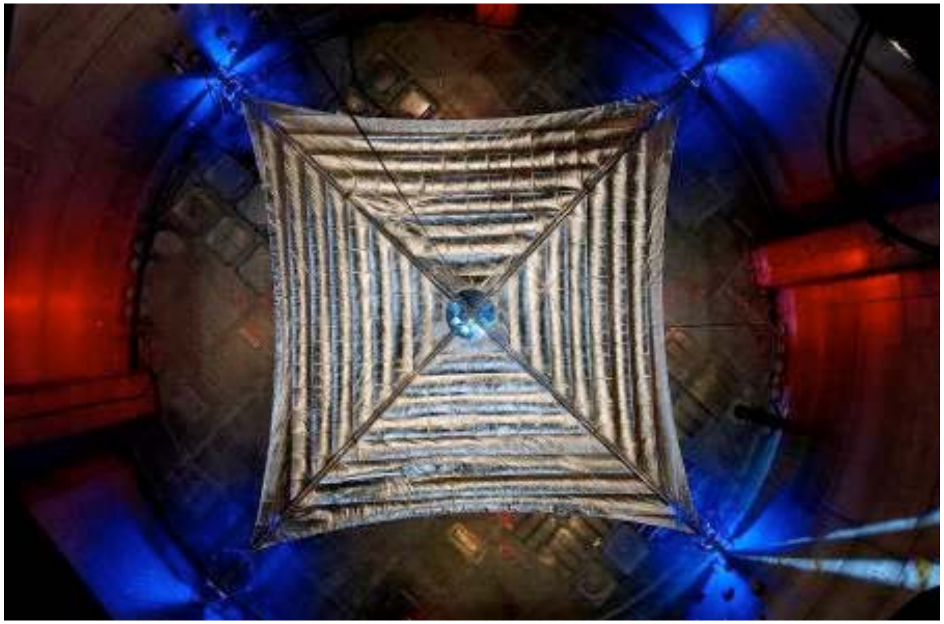
- Example mission design
  - Delta II 7425 launch (719 kg cap. to C3=0)
  - Flight system launch mass: 564 kg
  - Solar sail trajectory targeted for nose of heliosphere
  - 0.25 AU solar pass, 200 AU in 15 yrs.
- Flight system concept
  - Solar sail: < 1 g/m^2 , 200 m radius
  - "Flying Antenna" design implementation (191 kg)
  - Sized for 30 year operations
  - Payload: fields & particles + Imaging

Science Objectives

- Explore interstellar medium and determine directly the properties of the interstellar gas, the interstellar magnetic field, low-energy cosmic rays, and interstellar dust
- Determine structure & dynamics of heliosphere as example of interaction of a star with its environment
- Study, in situ, structure of solar wind termination shock, & acceleration of pickup ions & other species
- Investigate origin and distribution of solar-system matter beyond the orbit of Neptune


Current Technology

Solar Sails Technology Status



♦**General Description:**

- Propellantless propulsion utilizes solar photon pressure (<9 Newtons/km2) to obtain thrust. Sail film is compactly stowed for launch and deployed / supported by ultra-light weight trusses.

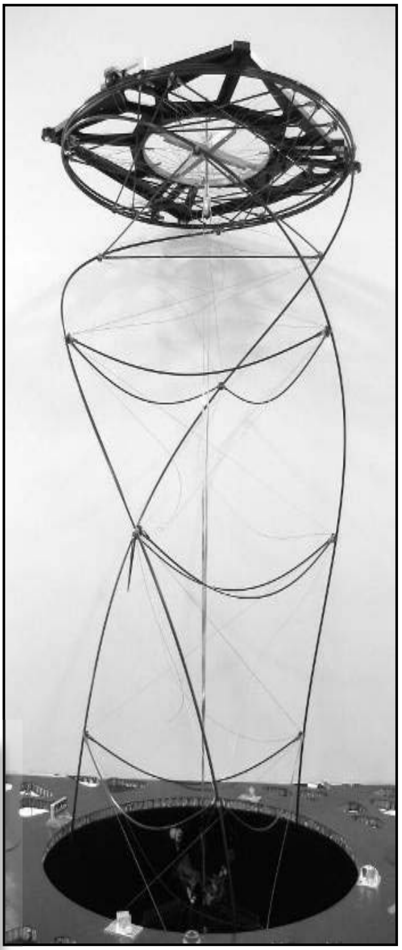
♦**Technology Benefits:**

- No propellants required
- Low system complexity (challenge is scaling to large area with ultra-low density)
- Low environmental impact on payload
- Enables access to previously inaccessible orbits (e. g., non-Keplerian, fixed reference, and high inclination orbit changes)

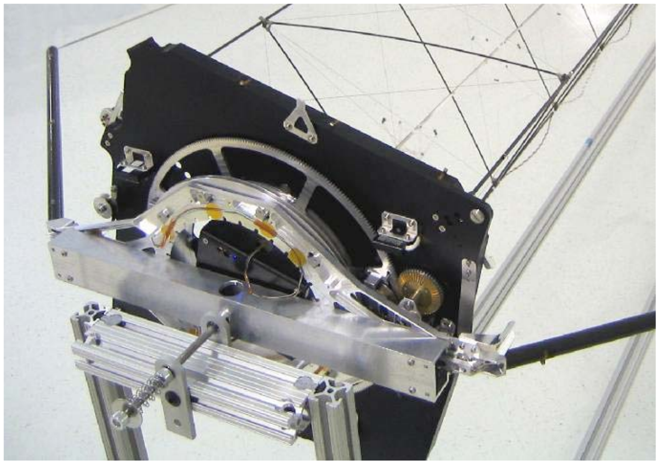
♦**Technology Area Status:**

- Two parallel awards to design, fabricate, and test competing sail concepts for system level ground demonstration:
  - 10 m system ground demonstrators were developed and tested in 2004.
  - 20 m system ground demonstrators designed, fabricated, and tested under thermal vacuum conditions in 2005.
- Multiple awards to develop and test high-fidelity computational models, tools, and diagnostics.
- Multiple awards for materials evaluation, optical properties, long-term environmental effects, charging issues, smart adaptive structures.

ATK Task Summary

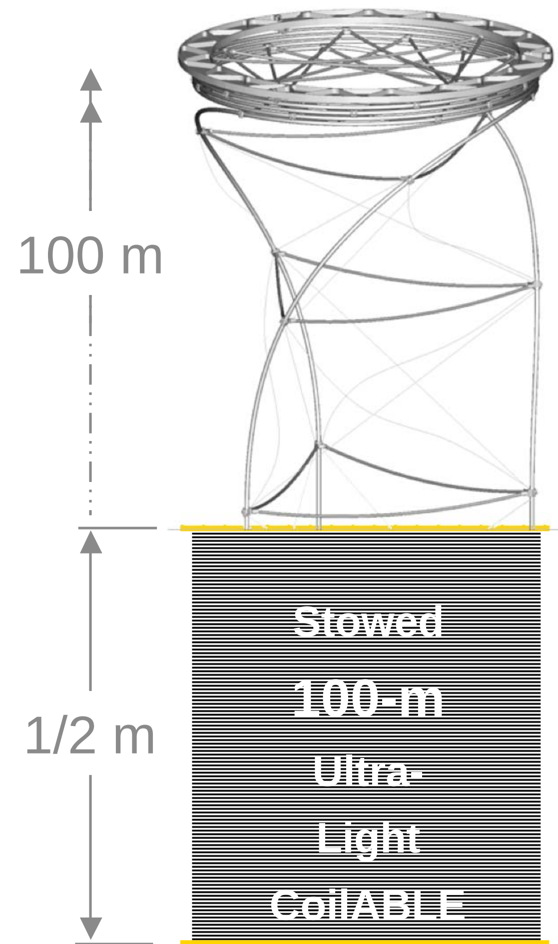


- PI: David Murphy, ATK Space Systems
- Proposal Team:
  - ATK (Goleta, CA) systems engineering & coilable booms
  - SRS Technologies (Huntsville, AL): Sail manufacture & assembly
  - LaRC (Hampton, VA) Sail Modeling & Testing
  - MSFC (Huntsville, AL) Materials Testing
- Overall Strategy
  - Leverages ST 7 Phase A Design
    - Improve performance with Ultra-Light Graphite Coilable booms
      - Synergy with SailMast Testbed selected to fly on ST8
    - Sail membrane, AL coated 2-4 μm CP1, compliant border, 3 point attach
    - Thrust Vector Control uses sliding masses along boom with spreader bars and micro-PPT at mast tip

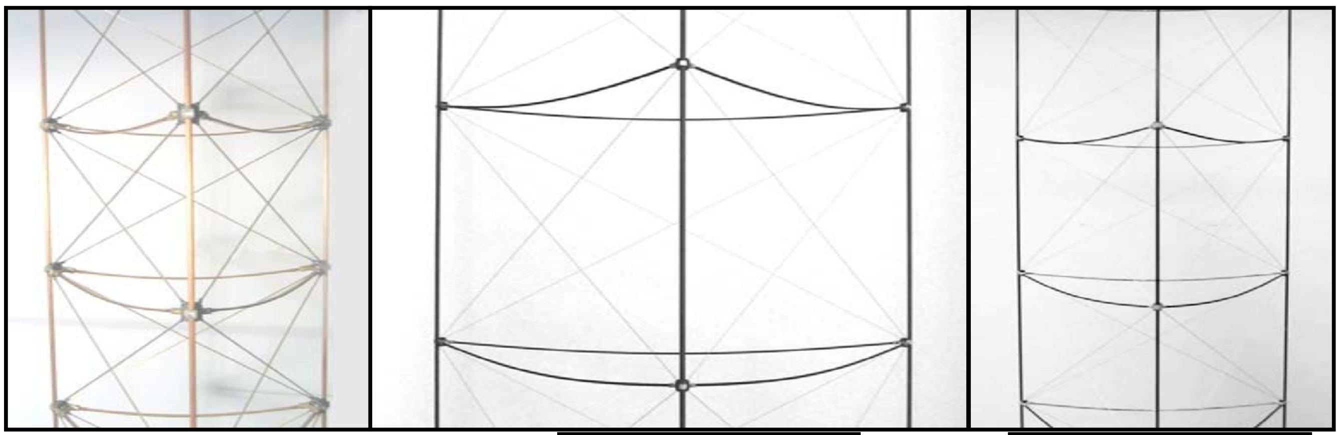


CoilAble Mast Heritage

- Able Engineering Company Established in 1975 (now ATK Space Systems)
  - 30 CoilAble systems have been flown to date
  - A phenomenal Stiffness to Weight ratio, High Dimensional Stability, Robust deployment, and Compact Stowage
- **Recent flight mast designs**
  - Mars Pathfinder (1999) 1-meter boom: 130 g/m
  - IMAGE spacecraft (2000) 10-meter booms: 93 g/m
- 100% Product Success Rate With No On-Orbit Failures



LACE | ISP | ST8

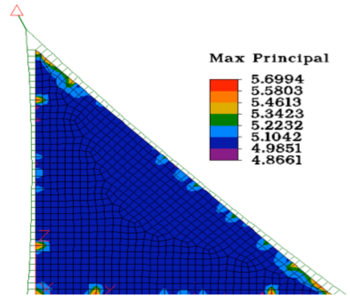


LACE	ISP	ST8
$\varnothing_M$ = 25.5 cm	$\varnothing_M$ = 39.5 cm	$\varnothing_M$ = 24.0 cm
L_S/L_D = 2.0%	L_S/L_D = 0.85%	L_S/L_D = 0.88%
ρ_L = 240 g/m	ρ_L = 70 g/m	ρ_L = 34 g/m

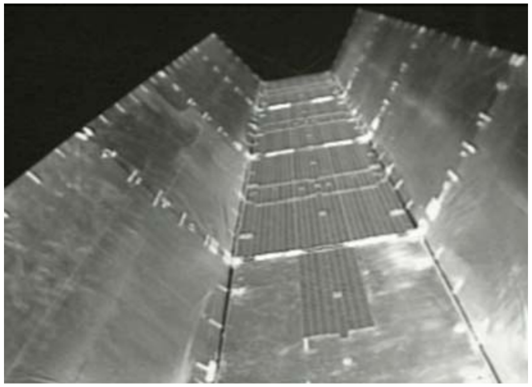
SRS Solar Sail Membrane Features

Membrane Design:

4-quadrant planar sail - 3-point sail attach with scalloped edges
- Designed determinant features, Biaxial membrane Design
- Compliant Border interface between edge cable and membrane
  - Shear insensitive, Cord/Material CTE mismatch insensitive
  - Thermal Gradient insensitive



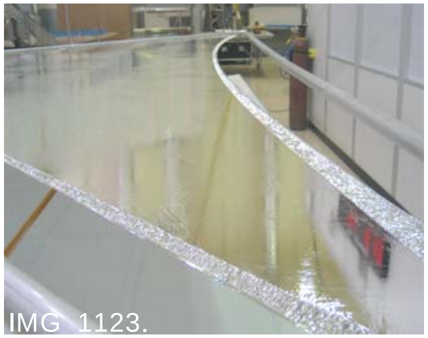
FEM of Parobolic Edge



160 m^2 of film per satellite. Film Is 1 mil material supported by 5 mil edge designs

Sail Material: *CP1 Polyimide*

- High Operating Temperature (>200° C)
- UV Stable
- Essentially Inert
- Soluble (Wet Process), modifiable with variety additives - improve conductivity and thermal properties
- ***~2 micron polyimide***
- ***Flight Proven --- flying on Numerous GEOCOM satellites***

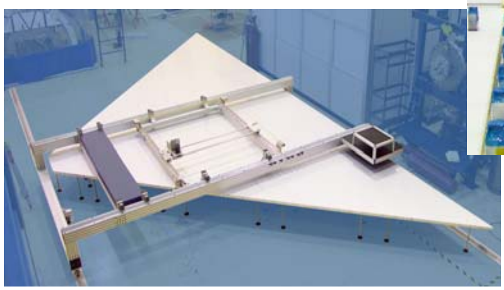


Sail with Compliant Border

Sail Construction Methods:

A gossamer film construction similar to gusseted, reflective blankets flying on numerous GEOCOM satellites
- Scalable Construction Methods --- current system >20m
- Adhesive less Bonding Methods --- eliminates sticking and contamination risks.

Sail Production

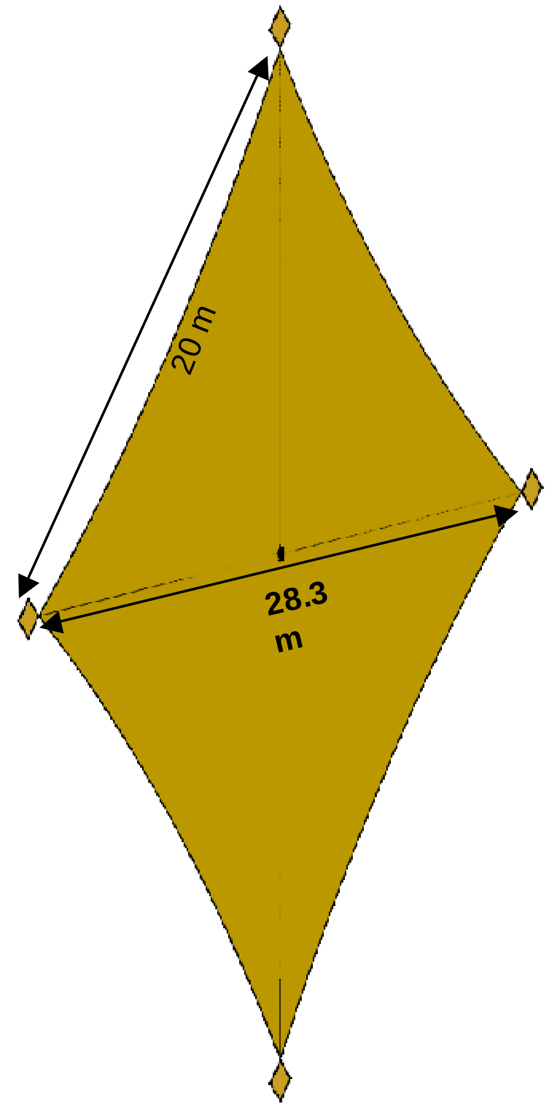


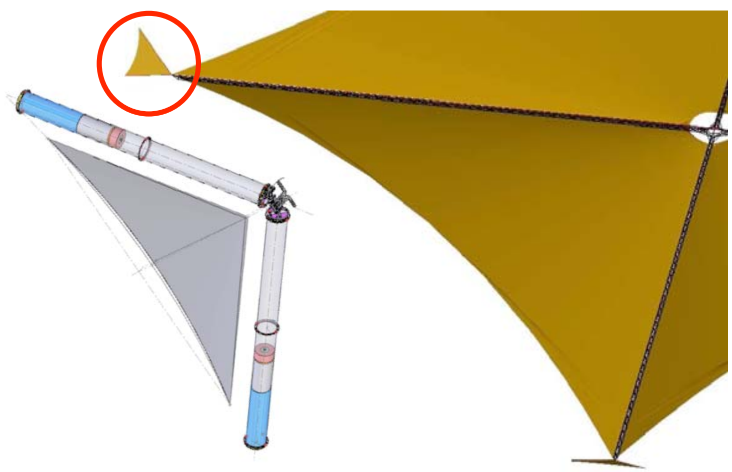
SRS CNC Seaming System

ATK Ambient Deployment at Plum Brook

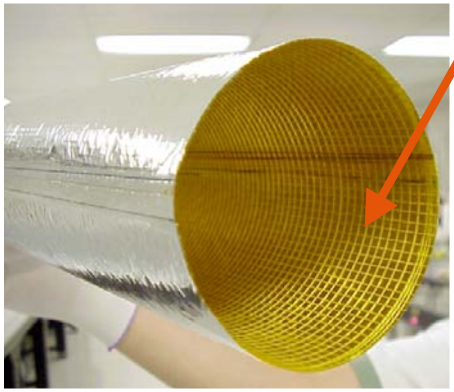
L'Garde Task Summary

- PI: David (Leo) Lichodziejewski, L'Garde, Inc.
- Proposal Team:
  - L'Garde, Inc. (Tustin, CA) systems engineering and inflatable truss
  - Ball Aerospace & Tech Corp. (Boulder, CO) mission eng. & bus design
  - LaRC (Hampton, VA) sail modeling & testing
  - JPL (Pasadena, CA) mission planning & space hazards
- Overall Strategy
  - Concept Leverages ST-5 Phase A and Team Encounter experience
    - Sail membrane, AL coated 2 μm Mylar attached with stripped net
    - Lightweight Semi-monocoque Boom With Sub-Tg Rigidization
    - 4 Vane Thrust Vector Control





Beam Design

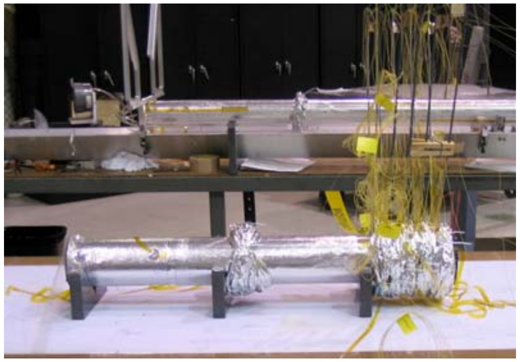


Load bearing longitudinal uni-directional fibers
- Fibers impregnated with sub-Tg resin (rigid below -20º C)
- 0.48 AU design requires greater fiber density to withstand loads from the increased solar flux

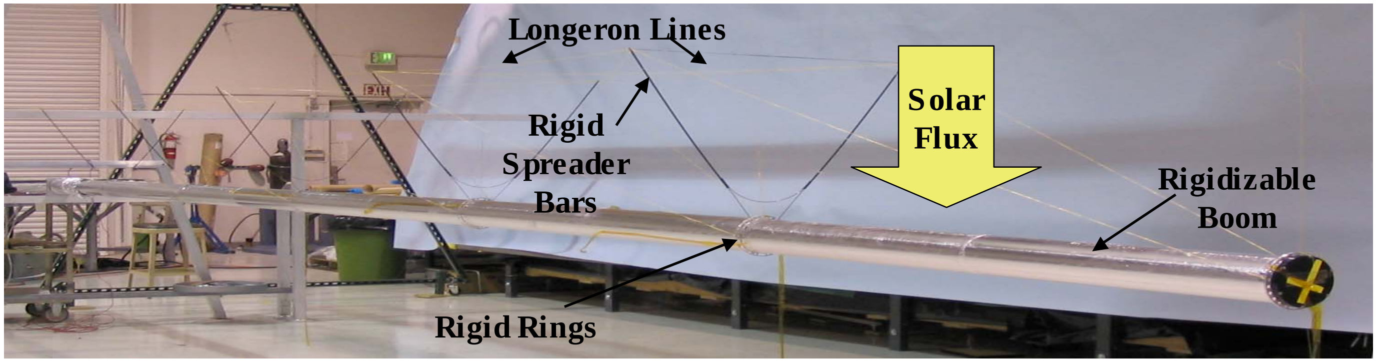
Spiral wrap
- Stabilizes longitudinal fibers
- Allows over-pressurization for deployment anomalies

Bonded Kapton bladder and Mylar
- Encapsulation "skin" carries shear
- Aircraft fuselage like structure

Beam Structure
- Sail structure is stressed for solar loading in one direction for mass efficiency
- Truss system comprised of mostly tension elements, minimal rigid components
- Highly mass efficient, ~36g/m linear density

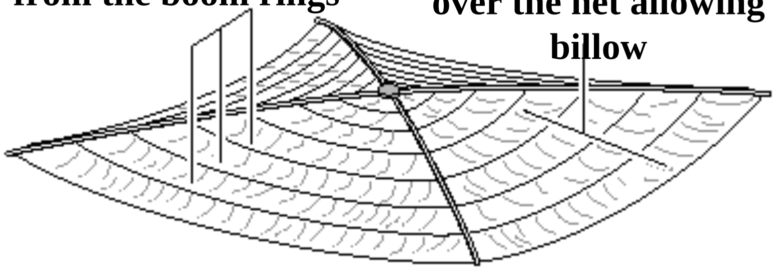


Stowed 7 m boom (~.5 m)



Deployed 7 m boom

Net/Membrane Sail Design



Net/Membrane Sail Schematic

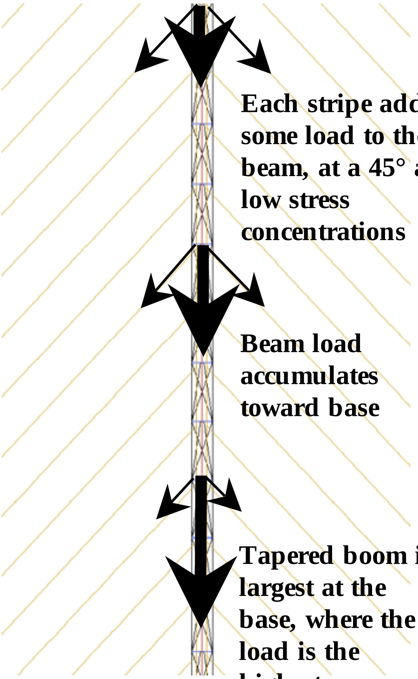
20m Sail Quadrant

Net Membrane

- Sail is supported by a high modulus, low CTE net, additional membrane material allows thermal compliance
- Sail properties effect local billow between net members only, global sail shape is stable

Advantages

- Net defines the overall sail shape, not the membrane
- Stability and geometry of the sail is effectively decoupled from membrane properties
- Sail shape, and hence thrust vector, sailcraft stability and performance, are predictable and stable
- No high local stress concentrations in the sail, loads are transferred though the net, not the membrane
- Very scalable, larger net/membrane sails simply add additional net elements to control overall shape



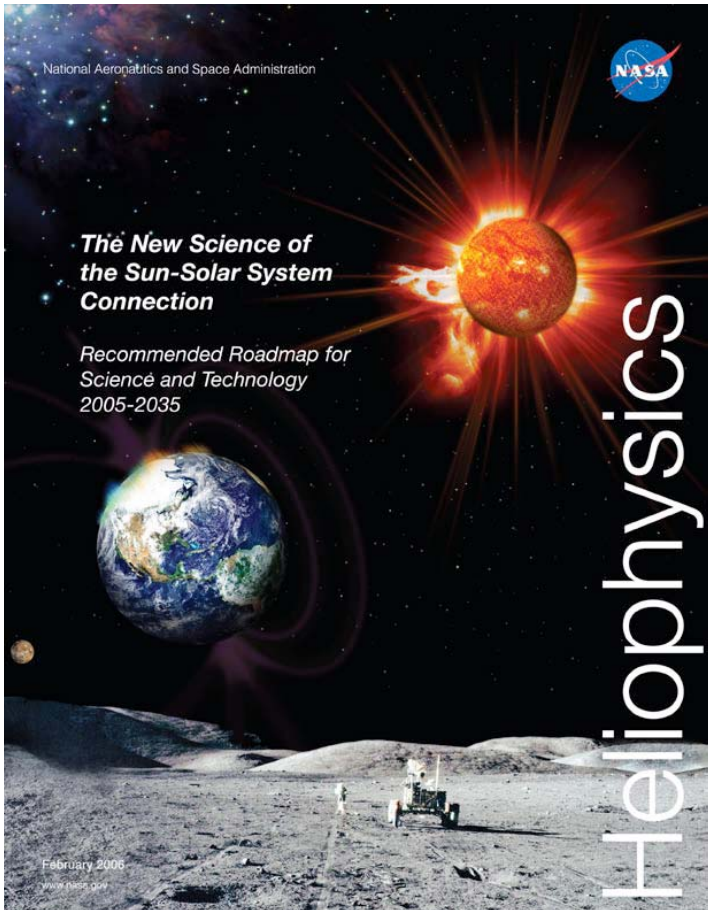
L’Garde 20m GSD Vacuum Deploy

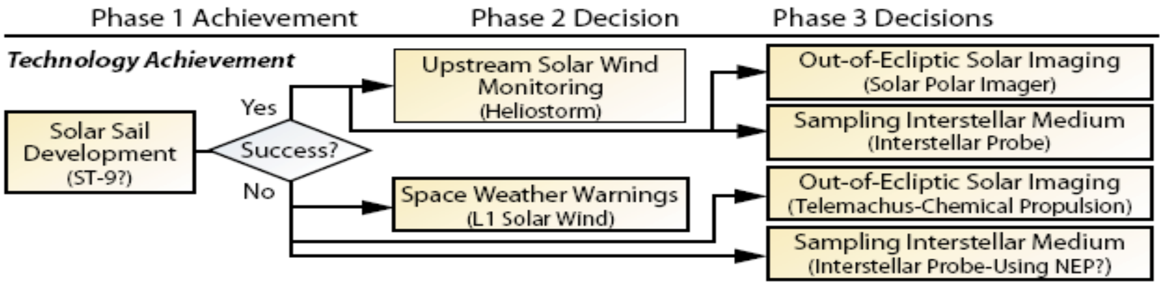
Solar Sails Notables

- Designed, built, delivered, and safely tested in a ground environment two 20m solar sail systems using different technologies
- Subjected materials to high doses of radiation verifying on-orbit life time characteristics
- Developed a flight mechanics simulation capable of modeling non-Keplerian orbits
- Conducted static and dynamic response tests and multiple deployments of two 400 square meter sails from a one square meter box at a high vacuum in the largest horizontal space test chamber in the world (Plum Brook). 500 Gb of data generated.
- Subjected stowed systems to launch loads and ascent vent tests prior to deployment.
- Modal Test Frequencies measured matched predicted values to within ten percent.
- Developed repair techniques for membranes and booms.
- Developed and used in test the largest high resolution photogrammetric shape measurement system in the world.
- Developed a mission concept to extend warning times to Earth for damaging solar events from 30 minutes to 90 minutes.
- Successfully applied conventional finite element modeling techniques to large area gossamer space structures.
- Determined the extent to which gossamer structures can be verified by test on the ground.
- Identified a tendency for torsional dynamic modes in the booms to migrate to bending modes.
- Discovered that wrinkles and other small defects have small impact on propulsion performance.
- Discovered significant robustness against spacecraft charging.

Future Developments

Heliophysics Draft Roadmap – 5/2006





Solar Sail Demo (SSD) **page 62**

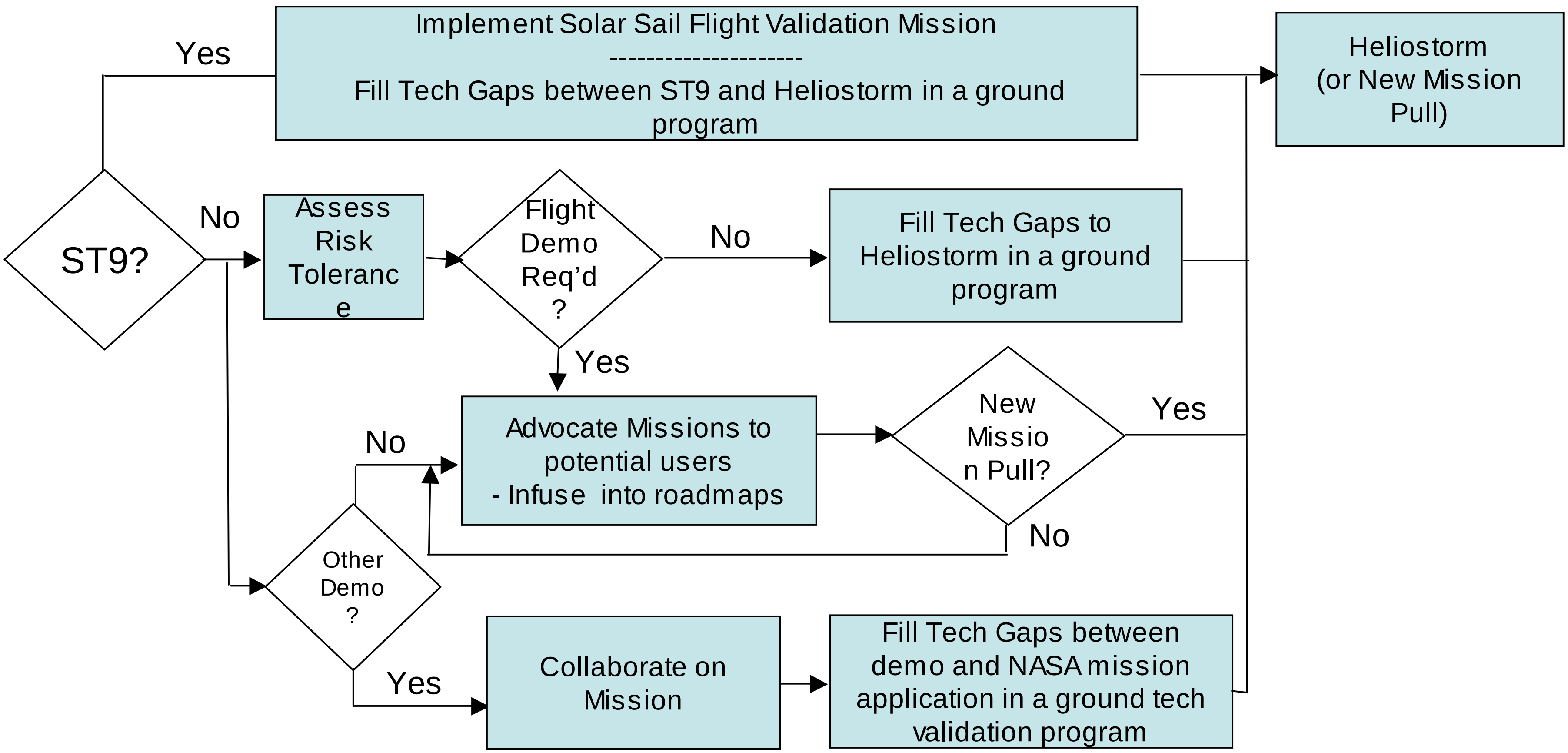
Because of the impossibility of fully validating Solar Sail technology on the ground, the application of solar sails to a strategic science mission **absolutely** requires a prior successful flight validation. **- page 93**

Heliostorm, in the LWS line, uses solar sails to hover twice as far up-stream as an L1 mission. **This is the preferred option.** The Helio-physics mission cost would be similar to an Explorer if NOAA and DoD partner with NASA. - **page 60**

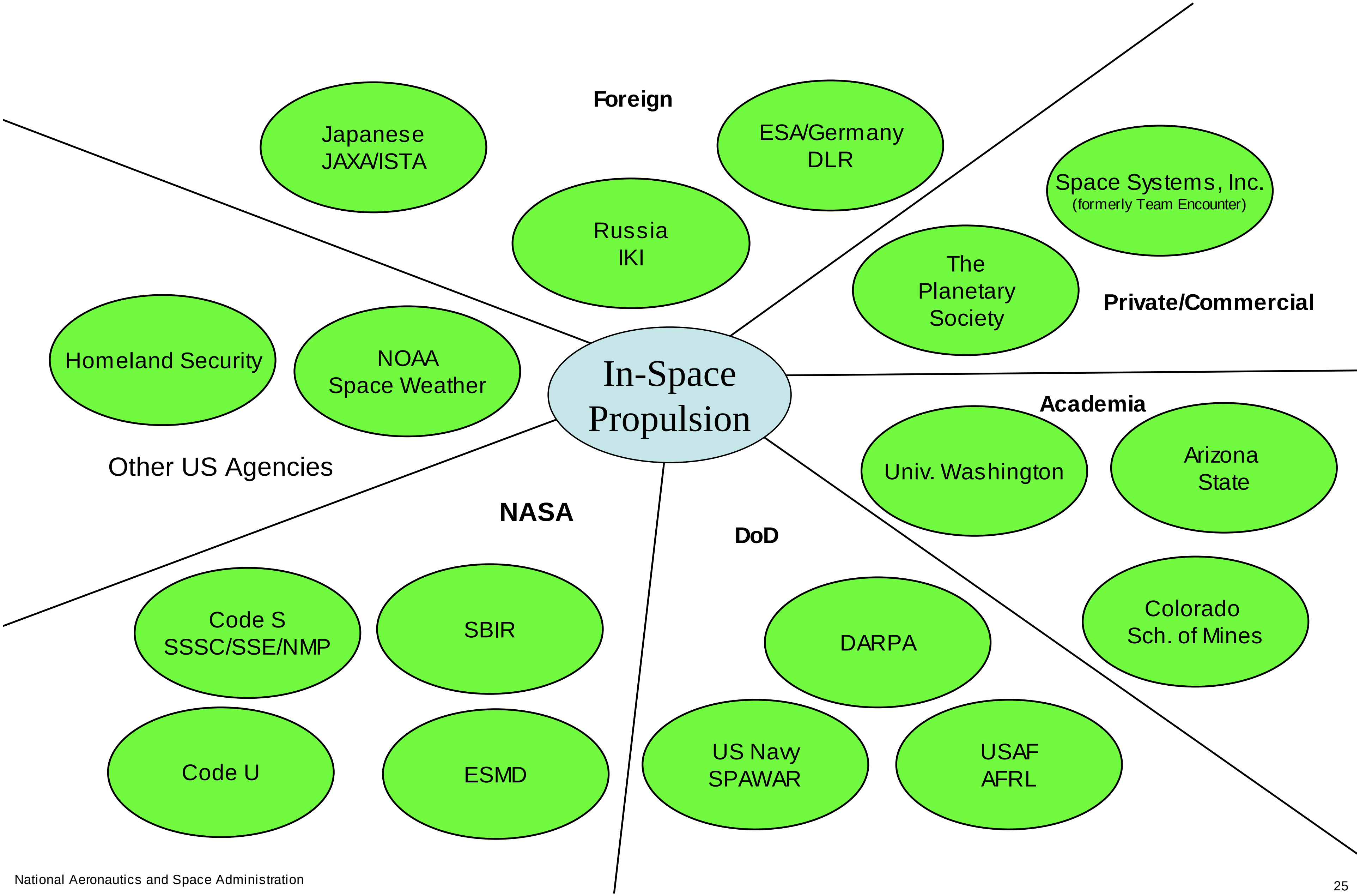
We encourage continued development of this technology *(solar sails)* and support the idea of a flight demonstration during Phase 1 of this Roadmap (CY 2005 – 2015). **- page 118**

Progress in key areas of Heliophysics science requires access to unique vantage points and in some cases, non-Keplerian orbits. For example, imaging of the Sun's polar regions requires a high-inclination, heliocentric orbit. Conventional technology would require either 5 years of solar electric propulsion and multiple Venus flybys just to reach a 38° inclination in the inner heliosphere (as for ESA's Solar Orbiter) or a Jovian gravity assist and conventional propulsion to provide an eccentric 0.25 x 2.5 AU polar orbit (as for our future Telemachus mission). **Neither means is as efficient or cost effective as solar sail technology. – page 97**

TRL Completion Logic



Growing Number of Solar Sail Activities



Technology Advantages

Low Cost to Develop & Operate

♦Simple

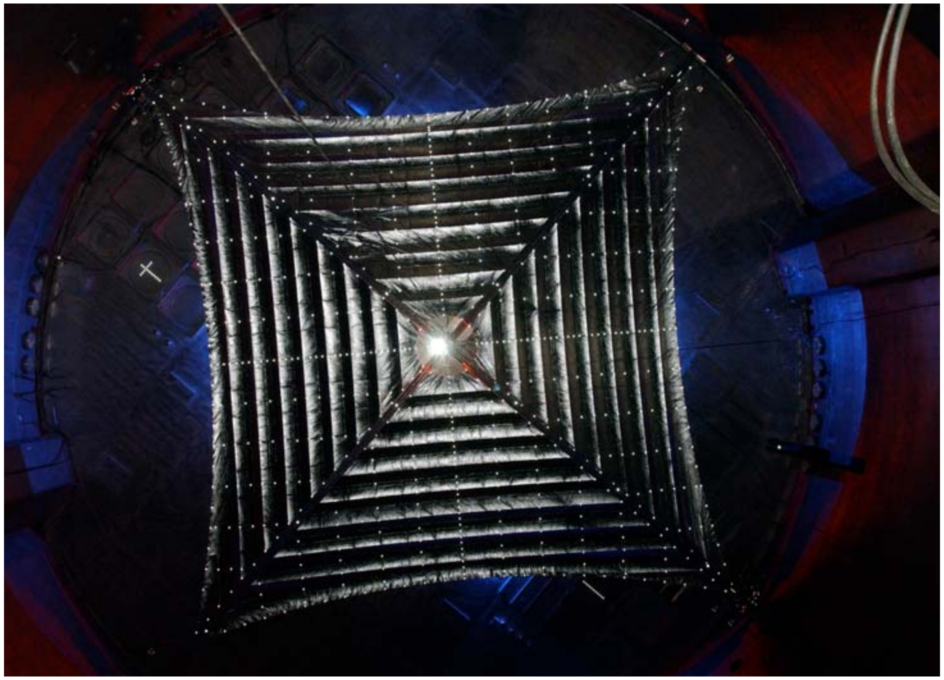
- Few moving mechanical parts
- Low complexity
- Quasi-Steady State
- Small in size – payloads and stowed system
- Autonomous, robotic

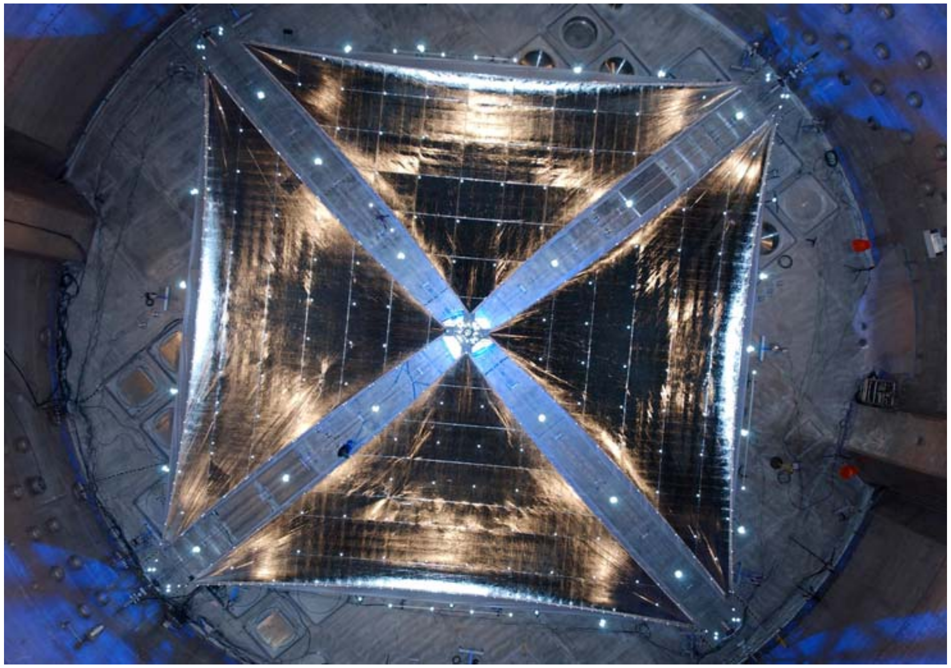
♦ Safe

- No High temperatures
- No High pressures
- No High Power
- No Toxic fuels
- Loads are vanishingly small

♦Technology Benefits

- No propellants required
- Low system complexity (challenge is scaling to large area with ultra-low density)
- Low environmental impact on payload
- Enables access to previously inaccessible orbits (e. g., non-Keplerian, fixed reference, and high inclination orbit changes)





For additional information on the Solar Sails Propulsion task areas within the In-Space Propulsion Technology Project, please contact:

Solar Sails – Catch the wave of the future!!!

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